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INVESTIGATION OF CORROSION-RESISTANT POLYMER COATINGS AND THEIR EFFECT ON THE OPERATIONAL PERFORMANCE OF VEHICLES

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Abstract:

Transport and technological machines operating under severe climatic and environmental conditions are highly susceptible to corrosion, which accelerates material degradation and reduces structural reliability and service life. Beyond its direct impact on durability, corrosion can alter surface integrity and mechanical properties of structural elements, potentially affecting vibration and noise characteristics within vehicle cabins. Elevated levels of noise and vibration in the driver's workspace are associated with reduced operator performance, increased fatigue, and potential long-term health risks. Therefore, improving both structural durability and vibroacoustic conditions represents an important engineering challenge. In this context, multifunctional anti-corrosion coatings, particularly polymer-based systems with viscoelastic properties, offer a promising approach. Such coatings are capable not only of providing corrosion protection but also of contributing to vibration attenuation through enhanced energy dissipation mechanisms. This study aims to evaluate the influence of epoxyurethane-based multifunctional anti-corrosion coatings on the vibration behavior of transport and technological machine cabins. The research combines analytical modeling and experimental investigations to assess changes in vibration response associated with coating application. The results indicate that the use of such coatings can contribute to a reduction in vibration amplitudes within specific frequency ranges, primarily due to increased damping. These findings highlight the potential of multifunctional coatings as a means of

simultaneously improving durability and vibroacoustic performance, although further studies are required for comprehensive validation.

Keywords: transport, technological machine, corrosion, coating, vibration, anti-corrosion coating, multifunctional coating.

Introduction

Corrosion is a physicochemical process involving the gradual degradation of materials due to chemical or electrochemical interactions with the surrounding environment [1]. It leads to progressive deterioration of structural integrity, reduction in mechanical strength, and eventual failure of engineering components. Although corrosion is most commonly associated with ferrous metals, it also affects non-ferrous alloys, concrete, and polymer-based materials [2].

The corrosion process typically evolves through several stages, including surface oxidation, formation of corrosion products, localized damage such as pitting, and ultimately severe structural degradation. Environmental factors such as humidity, temperature fluctuations, and the presence of aggressive agents (e.g., salts) significantly accelerate these processes, particularly under conditions involving periodic condensation of moisture [3].

To mitigate corrosion damage, a wide range of protection methods has been developed, including galvanic coatings, phosphating, thermal spraying, and organic or polymer-based coatings [4]. The evaluation of corrosion resistance and related indicators, including general corrosion, pitting, intergranular corrosion, and corrosion fatigue, is commonly carried out according to standardized methods [4].

Among various protection approaches, paint and varnish coatings are widely used in practice [5]. However, composite polymer coatings provide superior protective performance due to their enhanced physicochemical properties and durability [6]. Thermosetting polymers such as epoxy, polyester, phenol-formaldehyde, and furan resins are extensively applied for corrosion protection of metals and alloys [7,8]. Previous studies have also addressed corrosion protection of vehicle structures, including body panels and hidden cavities, through the development of specialized coating systems [9].

In addition to their protective function, polymer-based coatings exhibit viscoelastic behavior, which enables them to dissipate mechanical energy under dynamic loading. This phenomenon is described in terms of mechanical damping, defined as the ratio of dissipated energy to the maximum stored potential energy during a vibration cycle [10]

Experimental studies have demonstrated that the damping properties of polymer composites can be significantly enhanced by the incorporation of fillers. For example, the addition of aluminum powder particles has been shown to increase hysteresis losses and energy dissipation, which is associated with deformation energy per cycle and material softening behavior [11].In industrial and transport applications, vibration-damping composite coatings are widely used to reduce oscillations in structural elements [12]. This capability is attributed to the molecular structure of polymers, which exhibit both elastic and viscous responses. Unlike purely elastic materials, polymers do not store all deformation energy, and unlike purely viscous materials, they do not dissipate it completely, resulting in partial energy dissipation.

The vibration behavior of systems with hysteresis-type damping has been extensively studied, particularly in relation to reducing harmful oscillations in mechanical structures [13]

Despite these advances, the combined effect of anti-corrosion coatings on both durability and vibration characteristics of transport machine cabins remains insufficiently investigated. In particular, the extent

to which such coatings can simultaneously provide corrosion protection and enhance damping properties requires further study.

Moreover, prolonged exposure to vibration is known to adversely affect human operators, leading to fatigue, reduced performance, and musculoskeletal disorders. Therefore, reducing vibration levels in the driver's workspace is not only an engineering challenge but also a critical factor in occupational safety [14].

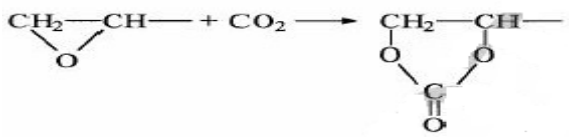
In this context, the present study aims to evaluate the influence of multifunctional epoxyurethane-based anti-corrosion coatings on the vibration behavior of transport and technological machine cabins [15].

Materials and method.

An advanced epoxyurethane-based anti-corrosion coating was synthesized using locally sourced raw materials and evaluated on transport and technological machines operating under harsh environmental conditions. The coating formulation incorporated specific additives to enhance its physicochemical, mechanical, and viscoelastic properties, which are critical for both corrosion protection and vibration damping.

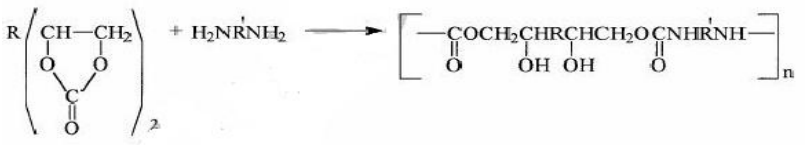
The synthesis procedure was performed in two stages:

1. **Cyclocarbonate synthesis**: Cyclocarbonates were generated via the chemical fixation of carbon dioxide onto epoxy oligomers:



(1)

2. **Epoxyurethane polymerization**: The epoxyurethane coating was formed by reaction of the cyclocarbonates with diamines, producing a cross-linked polymer network with tailored stiffness and damping characteristics:



(2)

The resulting anti-corrosion coating was applied to critical structural regions of the vehicle body and cabin floor with variable thicknesses. These regions were selected because they are the primary load-bearing surfaces that transmit vibrations from the chassis to the driver's seat. To quantitatively assess the influence of the coating on vibration transmission, a dynamic model of the "Human–Seat–Cabin–Protective Coating" system was developed based on Lagrange's equations of the second kind. The model integrates the viscoelastic behavior of the coating through modified damping and stiffness coefficients, representing its dual role in energy dissipation and structural reinforcement. **The schematic representation of the system is shown in Fig. 1.**

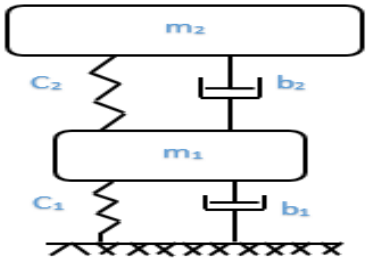


Figure. 1. Dynamic model of the "Human–Seat–Vibration–Protective Coating" system

where $m_1$is seat mass; $m_2$is human body mass; $C_1$is stiffness coefficient of the seat; $C_2$is stiffness coefficient of the human body model; $b_1$is damping (viscosity) coefficient of the seat model; $b_2$is damping (viscosity) coefficient of the human body model.

The governing Lagrange equation is:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{X}_i}\right) - \frac{\partial T}{\partial X_i} + \frac{\partial \Pi}{\partial X_i} + \frac{\partial \Phi}{\partial \dot{X}_i} = 0, \quad (3)$$

where T is kinetic energy of the system; Π is potential energy of the system; Φ is dissipation function; X_i are generalized coordinates.

The system energies are expressed as:

$$T = \frac{1}{2}m_1 \dot{X}_1^{\,2} + \frac{1}{2}m_2 \dot{X}_2^{\,2} \quad (4)$$

where $\dot{X}_1$, $\dot{X}_2$ are the linear speeds of the seat and the human respectively.

The potential energy of the model has the form:

$$\Pi = \frac{1}{2}C_1 X_1^2 + \frac{1}{2}C_2 (X_2 - X_1)^2, \quad (5)$$

where X_1, X_2 are generalized coordinates.

The dissipative function has the form:

$$\Phi = \frac{1}{2}b_1 \dot{X}_1^2 + \frac{1}{2}b_2 \left(\dot{X}_2 - \dot{X}_1\right)^2. \quad (6)$$

Derivatives of kinetic, potential, and dissipative terms:

$$\frac{\partial \mathrm{T}}{\partial \dot{X}_1} = m_1 \dot{X}_1; \ \frac{\partial \mathrm{T}}{\partial \dot{X}_2} = m_2 \dot{X}_2; \ \frac{d}{dt}\left(\frac{\partial \mathrm{T}}{\partial \dot{X}_1}\right) = m_1 \ddot{X}_1; \ \frac{d}{dt}\left(\frac{\partial \mathrm{T}}{\partial \dot{X}_2}\right) = m_2 \ddot{X}_2;$$

$$\frac{\partial \Pi}{\partial X_1} = C_1 X_1 - C_2 (X_2 - X_1); \ \frac{\partial \Pi}{\partial X_2} = C_2 (X_2 - X_1); \quad (7)$$

$$\frac{\partial \Phi}{\partial \dot{X}_1} = b_1 \dot{X}_1 - b_2 \left(\dot{X}_2 - \dot{X}_1\right); \ \frac{\partial \Phi}{\partial \dot{X}_2} = b_2 \left(\dot{X}_2 - \dot{X}_1\right).$$

Substituting into (3), the coupled equations of motion are:

$$m_1 \ddot{X}_1 + b_1 \dot{X}_1 - b_2 \left(\dot{X}_2 - \dot{X}_1\right) + C_1 X_1 - C_2 (X_2 - X_1) = 0;$$

(8)

$$m_2 \ddot{X}_2 + b_2 \left(\dot{X}_2 - \dot{X}_1\right) + C_2 (X_2 - X_1) = 0.$$

Normalized form for amplitude analysis:

$$\ddot{X}_1 = -b_{11} \dot{X}_1 + b_{22} \mu \left(\dot{X}_2 - \dot{X}_1\right) - n_1^2 X_1 + n_2^2 \mu (X_2 - X_1);$$

(9)

$$\ddot{X}_2 = -b_{22}\left(\dot{X}_2 - \dot{X}_1\right) - n_2^2(X_2 - X_1),$$

where

$$\mu = \frac{m_2}{m_1}; b_{11} = \frac{b_1}{m_1}; b_{22} = \frac{b_2}{m_2}; n_1^2 = \frac{C_1}{m_1}; n_2^2 = \frac{C_2}{m_2}.$$

The amplitude ratio is calculated using the differential operator method:

$$\frac{X_2}{X_1} = \frac{n_2^2 + i\omega b_{22}}{n_2^2 + i\omega b_{22} + \omega^2}, \qquad (10)$$

where $i^2 = -1$; ω is frequency.

This formulation quantitatively captures the **effect of the coating's viscoelasticity on vibration transmission**, allowing predictive analysis of vibration reduction at the driver's seat [19]. By adjusting coating thickness and material properties, it is possible to optimize damping and enhance operator comfort and safety.

Results and discussion.

The numerical simulation and experimental validation were conducted using Maple 18 software. The following parameters were assigned to the system based on standard anthropometric data and vehicle specifications:

m_1= 750 kg, m_2= 75 kg, b_1=100 kg/s, b_2=10 kg/s, C_1=200000N/m, C_2=300000 N/m.

Experimental studies were performed on Isuzu and MAN trucks operating along the Qamchiq mountain pass, which presents a highly variable terrain with frequent excitations in multiple frequency ranges [16], [17]. The lower sections of the cabin floors were coated with epoxy–polyurethane-based composite layers of varying thicknesses to assess their damping efficiency in real operating conditions. Vibration measurements were recorded using high-precision accelerometers installed at the seat and floor interface [18], [19].

Using the system of equations (9), amplitude–frequency characteristic curves were generated to investigate the dynamic response of the "Human–Seat–Coating" system. These curves quantify the influence of coating thickness and material properties on vibration amplitudes across a range of excitation frequencies.

The results are presented in Fig. 2.

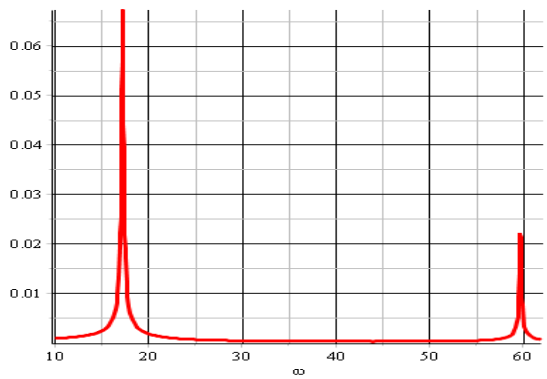


Figure. 2. Amplitude–frequency characteristics of the "Human–Seat–Coating" system

From the analysis of amplitude–frequency characteristics, several key observations were made. Resonance peaks occur near the natural frequencies of the seat and the human body. This is consistent with classical vibration theory, where maximum response amplitude is observed at structural resonance. Seat resonance dominates the transmitted vibration spectrum, with amplitudes significantly higher than those corresponding to the human body's natural frequency. This suggests that seat stiffness and damping are primary factors influencing vibration transmission to the driver. Effect of coating thickness: Increasing the composite coating thickness led to a noticeable reduction in peak vibration amplitudes [20]. This is attributed to enhanced viscoelastic damping provided by the epoxy–polyurethane layer, which dissipates mechanical energy and reduces the resonance intensity. The frequency shift of resonance peaks with coating application indicates a slight increase in effective system stiffness (C_1 and C_2), demonstrating the dual role of the coating in corrosion protection and vibration mitigation [21].

The observed reduction in vibration amplitude demonstrates the functional synergy of multifunctional coatings:

Corrosion resistance preserves the structural integrity of the cabin floor, preventing stiffness degradation over time.

Energy dissipation reduces vibration transmission, enhancing operator comfort and decreasing the risk of fatigue-related accidents.

This experimental-theoretical approach confirms that careful selection of coating material properties (modulus, damping factor, thickness) can optimize both service life extension and vibration mitigation in transport and technological machines operating under harsh conditions.

Conclusion

In the Republic of Uzbekistan, transport and technological vehicles frequently operate under highly demanding environmental conditions, including mountainous terrain, quarries, foothill regions, and desert areas. These environments subject vehicles to extreme thermal fluctuations, mechanical shocks, abrasive dust, and the widespread use of salt-containing anti-icing agents during winter months. In desert regions, high soil salinity further exacerbates the risk of corrosion. Collectively, these factors accelerate structural degradation, reduce service life, and compromise operational safety.

Experimental evaluation revealed that vibration amplitude values for coatings of varying thicknesses ranged from 0.053 to 0.068, confirming that increasing coating thickness correlates with improved damping performance. These results validate the effectiveness of multifunctional coatings in harsh operational conditions, highlighting their potential to enhance both vehicle longevity and operator safety.

Overall, the findings of this study provide a practical framework for optimizing coating properties in transport and technological machines, ensuring that vehicles remain reliable and ergonomically safe in challenging environments.

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